NONISOTHERMAL MODELING OF SHORT-TERM TEST CYCLES

A three-dimensional, anisotropic, nonisothermal, ground-water-flow and thermal-energy-transport model was used to simulate the four short-term test cycles. The model has the same discretization as the preliminary three-dimensional, isothermal ground-water-flow model described by Miller and Delin (1993). Miller and Voss (1986) describe discretization of the model and the sensitivity of the lateral boundary conditions for various rates of heated-water injection.

The finite-difference, ground-water-flow, and thermal-energy-transport model used in this study was developed for waste-injection problems (Intercomp Resources Development and Engineering, 1976) and will be referred to in this report as the Survey Waste Injection Program (SWIP) code. The SWIP code can be used to simulate ground-water flow and heat and solute transport in a liquid-saturated porous medium; it contains both reservoir and well-bore modeling capabilities.

The major model assumptions are as follows:

1. Ground-water flow is laminar (Darcy), three dimensional, and transient.
2. Fluid density is a function of pressure, temperature, and concentration.
3. Fluid viscosity is a function of temperature and concentration.
4. The injected fluid is miscible with the in-place fluids.
5. Aquifer properties vary with location.
6. Hydrodynamic dispersion is a function of fluid velocity.
7. The energy equation can be described as: enthalpy in minus enthalpy out equals the change in internal energy of the system.
8. Boundary conditions allow natural water movement in the aquifer and heat losses to adjacent formations.
9. Thermal equilibrium exists within the simulated area.

The basic equation describing single-phase flow in a porous medium is derived by combining the continuity equation and Darcy equation for three-dimensional flow (Intercomp Resources Development and Engineering, 1976, p. 3.4):

$$\nabla \bullet \left[\frac{\rho k}{\mu}(\nabla p - \rho g \nabla z)\right] - q' = \frac{\partial}{\partial t}(\phi\rho) \qquad (1)$$

where

ρ = fluid density [M/L^3] (kg/m^3),
μ = fluid viscosity [M/L-T] (kPa-s),
k = intrinsic permeability [L^2] (m^2),
g = gravitational acceleration [L/T^2] (m/s^2),
z = spatial dimension in direction of gravity [L](m),
p = pressure [M/L-T^2] (kPa),
q' = mass rate of flow per unit volume from sources or sinks [M/T-L^3] (kg/s-m^3),
t = time [T] (s),
ϕ = porosity [dimensionless], and
∇ = gradient (for an axially symmetric cylindrical coordinate system ∇ is

$$\frac{\partial}{\partial r} + \frac{1}{r}\frac{\partial}{\partial \theta} + \frac{\partial}{\partial z}$$

where r is the radial dimension).

The energy-balance equation describing the transport of thermal energy in a ground-water system (Intercomp Resources Development and Engineering, 1976, p. 3.4) is:

$$\nabla \bullet \left[\frac{\rho k}{\mu}H(\nabla p - \rho g \nabla z)\right] + \nabla \bullet K \bullet \nabla T - q_L - q'H = \frac{\partial}{\partial t}[\phi\rho U + (1-\phi)(\rho C_p)_R T] \qquad (2)$$

where

H = enthalpy per unit mass of fluid [E/M] (J/kg),
K = hydrodynamic thermal dispersion plus convection [E/T-L-t] (W/m-°C),
T = temperature [t] (°C),
q_L = heat loss across boundaries [E/T] (W)
U = internal energy per unit mass of fluid [E/M] (J/kg),
$(\rho C_p)_R$ = heat capacity of aquifer matrix [E/L^3-t] (J/m^3-°C), and
C_p= specific heat of aquifer matrix [E/M-t] (J/kg-°C)
(All other terms are previously defined.)

Equations 1 and 2 are a nonlinear system of coupled partial-differential equations that is solved numerically by discretizing the aquifer into three dimensions (or two dimensions for radial flow) and developing finite-difference approximations.

Finite-difference equations (Intercomp Resources Development and Engineering, 1976, p. 3.5) whose solutions closely approximate the solutions of equations 1 and 2 are, for the basic flow equation:

$$\Delta[T_w(\Delta p - \rho g \Delta z)] - q = \frac{V}{\Delta t}\delta(\phi\rho) \qquad (3)$$

and for the energy equation:

$$\Delta[T_w H(\Delta p - \rho g \Delta z)] + \Delta(T_c \Delta T) - q_L - qH =$$